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EFFECT OF HEATING RATE ON CHAR YIELD FROM FOREST FUELS

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ABSTRACT

Char yield at 500° C has been measured for 40 typical forest fuels, including foliage, wood, small stems, and bark. The effect of changing heating rates was determined from 20° C/min to about 1000° C/min, to simulate a range of burning conditions. The average of all fuels was 26.7 percent char at 20° C/min, decreasing to 23.9 percent at the highest rate. Each of the fuel types gave a similar small decrease in char yield as heating rate increased. Relative char yields for individual fuels, which can be used to compare flaming or glowing combustion tendencies, are nearly independent of heating rate.

KEYWORDS: forest fuels, char yield, heating rate.

Mathematical models, which have been developed to predict fire behavior in forest fuels, recognize both flaming and glowing combustion mechanisms of heat release from the fuels (Rothermel 1972; Albini 1980). Flaming combustion requires volatile products released by heating the solid fuel. Glowing occurs in the solid carbonaceous product. Present models use the total heat of combustion as the heat source for spreading fire but do not separate the two mechanisms. Separating the heat of combustion of volatiles from that for char would allow a more detailed description of the fire, which could then be used in improved or new models. The amount of char formed depends in part on fuel chemistry (Rothermel 1976) and could provide a sensitive indicator of differences in fire behavior. High char yields, due to fuel chemistry or application of fire retardants, would limit fire spread to smoldering at the expense of flaming (Albini 1980). On the other hand, smoldering combustion can complicate fire behavior and is very difficult to suppress (Ohlemiller and others 1979).

Char fractions are easily measured by thermogravimetric analysis (TG). Commercial instruments provide rapid and precise analysis and can be applied to a wide variety of forest fuels. One problem with this method is that normal TG heating rates are far lower than rates expected in a fire. Therefore, the sensitivity of char formation to heating rate needs to be examined before TG measurements can be used in models of real fires.

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The fuel heating rate in a fire is highly variable, depending on the heat flux to the fuel, fuel particle size, and thermal diffusivity, among other factors. Even adjacent particles are likely to experience a range of heating rates. There seems to be little agreement on a representative heating rate for a "typical" fire. The ASTM E119 fire test for building material requires a surface heating rate of about 100° C/min to simulate building fires. McCarter (1972) used a 60° C/min rate to approach those in burning cellulose. Walker (1963) indicated surface heating rates of 250° to 500° C/min may be more representative of wildland fires. Thus, common TG rates of 5° to 20° C/min may be 10 to 100 times slower than those found in spreading fires. Although slower heating insures more accurate temperature measurements, the applicability to fire conditions needs to be verified.

Studies on cellulose (Broido and Nelson 1975), a component of forest fuels, showed a strong dependence of ultimate char yield on heating conditions. Rapid heating to 370° C resulted in about 12 percent char after 1 hour. In contrast, a 21-hour pretreatment at 275° C followed by heating to 370° C, produced more than 27 percent char. Extremely slow heating rates should also lead to increased char from cellulose. At very high heating rates (above 400° C/s) essentially all the cellulose can be converted to volatiles without char formation (Lewellen and others 1977).

The variations in char yield from cellulose have been attributed to competing reactions that favor charring at lower temperatures (Broido and Nelson 1975). Secondary charring of volatiles can also occur, depending on their residence time in the pyrolyzing cellulose matrix (Lewellen and others 1977). Similar variations due to heating rate have also been noted for wood pyrolysis (Lee and others 1977; Browne 1958). Variable char yield reported for forest fuels (Susott and others 1975) may have been due to the sensitivity of cellulosic components to heating rate.

The effect of heating rate on char yield from forest fuels components other than cellulose has not been determined, nor has charring of a wide range of fuels been studied. The objective of this study was to measure these effects for typical forest fuels. These fuel samples were available from a more extensive study of their thermal properties, which will be reported elsewhere.

EXPERIMENTAL METHODS

Samples.--The forest fuel samples used in this study are listed in table 1. Samples were selected to provide data on different parts of typical fuels found in wildland fires, including foliage, wood, small stems, and bark. Low-ash cellulose filter paper was included for comparison because considerable literature was available on its char formation.

In general, the green foliage and stem samples were frozen when collected and then freeze-dried to less than 10 percent moisture content. Wood, bark, and litter samples were air-dried at room temperature. All samples were ground to pass through a 20-mesh screen. Green samples were kept frozen prior to analysis.

Table 1.--*Forest fuel descriptions*

Number	Common name	Species	Part
1	Chamise	*Adenostoma fasciculatum* H. & A.	Foliage
2	Greenleaf manzanita	*Arctostaphylos glandulosa* Eastw.	Foliage
3	Big sagebrush	*Artemisia tridentata* Nutt.	Foliage
4	Gallberry	*Ilex glabra* (L.) Gray	Foliage
5	Utah juniper	*Juniperus osteosperma* (Torr.) Little	Foliage
6	Lodgepole pine	*Pinus contorta* Dougl.	Foliage
7	Pinyon pine	*Pinus edulis* Engelm.	Foliage
8	Slash pine	*Pinus elliotii* Engelm.	Foliage
9	Western white pine	*Pinus monticola* Dougl.	Foliage, dead
10	Ponderosa pine	*Pinus ponderosa* Laws.	Foliage
11	Ponderosa pine	*Pinus ponderosa* Laws.	Foliage, dead
12	Quaking aspen	*Populus tremuloides* Michx.	Foliage
13	Douglas-fir	*Pseudotsuga menzeisii* (Mirb.) Franco	Foliage
14	Black oak	*Quercus velutina* Lam.	Foliage, dead
15	White fir	*Abies concolor* (Gord. & Glend.) Lindl.	Wood
16	White fir	*Abies concolor* (Gord. & Glend.) Lindl.	Wood, rotten
17	Grand fir	*Abies grandis* (Dougl.) Lindl.	Wood
18	Excelsior	*Populus* spp. L.	Wood, dead
19	Larch	*Larix occidentalis* Nutt.	Wood
20	Larch	*Larix occidentalis* Nutt.	Wood, lumber
21	Ponderosa pine	*Pinus ponderosa* Laws.	Wood
22	Ponderosa pine	*Pinus ponderosa* Laws.	Heartwood lumber
23	Douglas-fir	*Pseudotsuga menzeisii* (Mirb.) Franco	Wood
24	Douglas-fir	*Pseudotsuga menzeisii* (Mirb.) Franco	Wood, lumber
25	Douglas-fir	*Pseudotsuga menzeisii* (Mirb.) Franco	Wood, rotten
26	Big sagebrush	*Artemisia tridentata* Nutt.	Stems
27	Utah juniper	*Juniperus osteosperma* (Torr.) Little	Stems
28	Pinyon pine	*Pinus edulis* Engelm.	Stems
29	Douglas-fir	*Pseudotsuga menzeisii* (Mirb.) Franco	Twigs
30	Utah juniper	*Juniperus osteosperma* (Torr.) Little	Bark
31	Larch	*Larix occidentalis* Nutt.	Bark
32	Ponderosa pine	*Pinus ponderosa* Laws.	Bark
33	Douglas-fir	*Pseudotsuga menzeisii* (Mirb.) Franco	Bark
34	Cheatgrass	*Bromus tectorum* L.	Aerial plant, cured
35	Idaho fescue	*Festuca idahoensis* Elmer	Aerial plant, cured
36	Braken fern	*Pteridium aquilinum* (L.) Kuhn	Fronds, cured
37	Saw palmetto	*Serenoa repens* (Bartr.) Small	Fronds
38	Tundra, interior	*Hylocomium splendens* Hedw. and *Pleurozium schreberi* (Brid.) Mitt.	Top layer of black spruce understory
39	Duff	--	"F" layer, dead
40	Cellulose	--	--

Thermogravimetric analysis.--A Perkin-Elmer TGS-2[2] thermogravimetric system was used in all analyses. A Hewlett-Packard data acquisition system measured sample mass to 0.1 ug and run time to 0.04 second. All data were digitized and stored on magnetic tape for postrun calculations. Furnace temperature was programmed by the data system through a digital-to-analog converter which presented the TGS-2 furnace control with either a voltage ramp, for runs at a fixed rate, or a constant voltage for isothermal runs at 500° C. Two or more replicate subsamples of 5 ± 0.5 mg were charred under nitrogen flowing at 0.2 liters/min to a final temperature at 500° C. Three heating rate programs were used. In the first, samples were heated at a constant rate of 20° C/min from room temperature to 500° C. The second program was like the first up to 140° C but then the rate was increased to 200° C/min. In the third program, the sample was first heated to 140° C at 20° C/min to drive off moisture. The furnace was then lowered away from the sample and heated at a rate of 300° C/min to 500° C. While the furnace was in the lowered position, the sample temperature remained below 160° C. The inert sample atmosphere was maintained by a plug sealing the glass outer tube to the antistatic tube around the hangdown wire. After a 3 minute period for temperature stabilization, the preheated furnace was quickly raised to its normal position around the sample.

For the first program, described above, residues were weighed when the program reached 500° C. For the second, the furnace was held at 500° C for 30 seconds to insure temperature uniformity before the residue was measured. For the third program, residues were weighed 30 and 50 seconds after the furnace was raised. Residues determined by the first method were corrected for a 30-second hold at 500° C by assuming a constant weight loss rate at 500° C, equal to the rate from 498° to 500° C.

Ash content was determined after residue measurements by changing the sample atmosphere to air flowing at 200 ml/min. The furnace was then programmed at 20° C/min to 600° C to burn off all carbonaceous char. The resulting residues were grey to white, indicating complete ashing. The ash contents were used to correct sample weight at 140° C and the residues at 500° C to an ash-free basis. Moisture contents were also determined from TG analysis by using the weight at 140° C as the dry sample weight. The heating rates to 140° C were kept equal for each program in order to obtain comparable dry samples.

The TG system temperature was calibrated by the Curie point method (Norem and others 1970) using the alumel, nickel, and nicoseal Curie points at 163°, 354°, and 438° C, respectively. Heating programs were accurate to within 2° C. Sample temperature deviated considerably from the programs during highly endothermic or exothermic pyrolysis reactions, but these reactions were minimal when the final char residues were measured.

Several representative fuel samples, containing added Curie point standards, were pyrolyzed in the preheated furnace (third program) to estimate the heating rate. Samples reached the nicoseal Curie point at 438° C in about 15 seconds for an average heating rate of over 1000° C/min through most of the thermal reactions.

RESULTS AND DISCUSSION

Typical changes due to increased heating rate are shown in figure 1, which details the TG results for greenleaf manzanita foliage. The time derivatives of the TG curves (DTG) are shown to emphasize changes in pyrolysis rates and temperatures. Increasing the heating rate from 20° C/min (curve A) to 200° C/min (curve B) caused a nearly 10-fold increase in weight loss rates. Features present at 20° C/min shifted to considerably higher temperatures in the 200° C/min scan. The shift could not be accurately measured, however, due to the variable effects of reaction enthalpy and changing heat capacity during weight loss.

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[2] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

Runs with the furnace preheated to 500° C (curve C) showed a further 10-fold increase in weight loss rate. These runs exhibited only one major weight loss peak, unlike runs with linear heating rates. This major reaction was essentially complete in 25 to 30 seconds for all samples studied. At the 200° C/min rate, the weight loss was also nearly completed after the 30 seconds hold at 500° C. The weight loss rates for runs at 20° C/min were typically less than 0.03 percent/s at the final temperature.

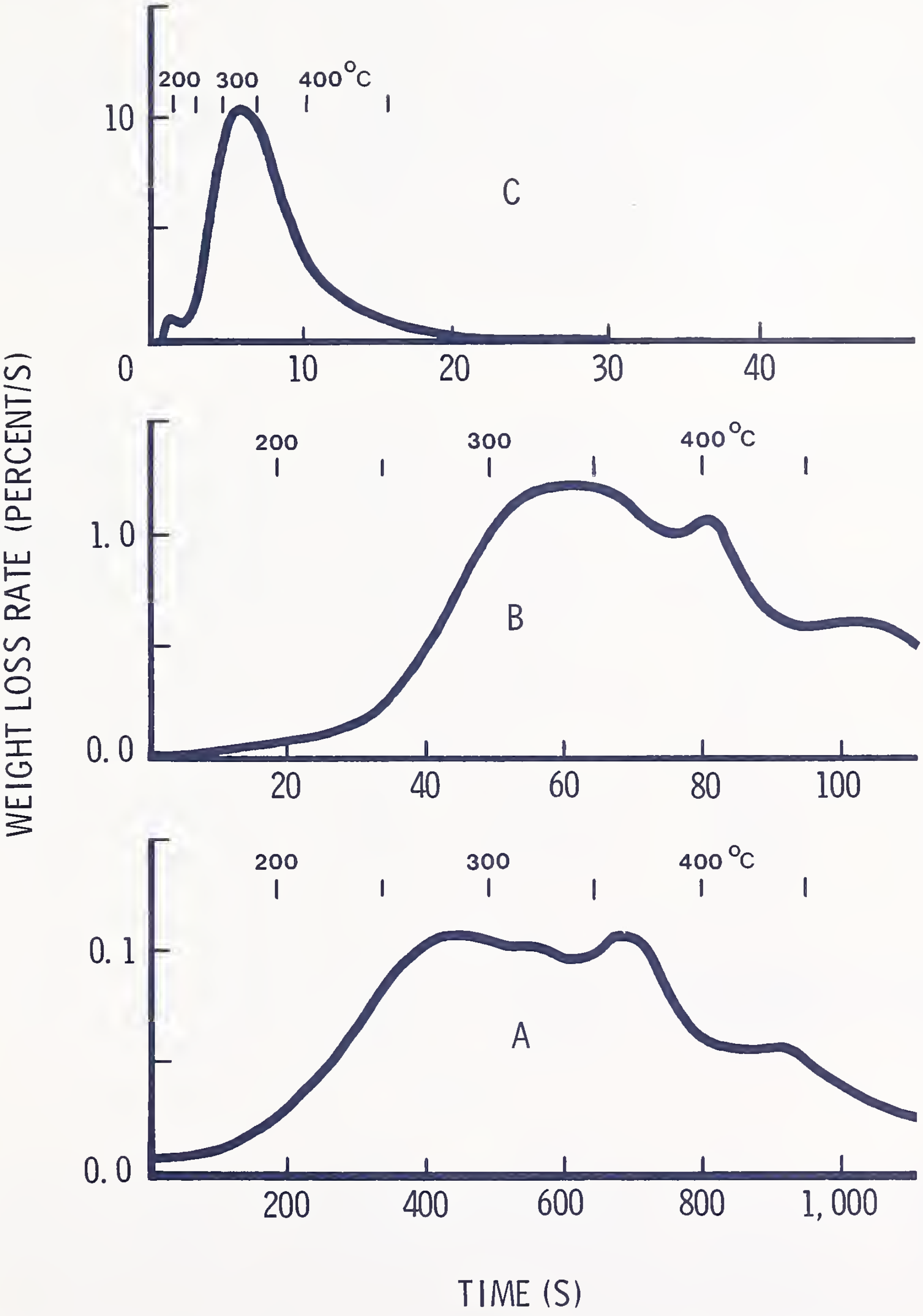

Figure 1.--Thermal analysis curves for greenleaf manzanita foliage at several heating rates: (A) 20° C/min; (B) 200° C/min; (C) sample placed in furnace preheated to 500° C. The approximate sample temperature were derived from TG curves for Curie point standards.

The curves in figure 1 show that pyrolysis was not complete, even at 500° C where weight continues to be lost. The weight loss rate was often one-third to one-half of the maximum rate, for runs made at the two linear heating rates. In spite of this, 500° C appears to be a reasonable temperature limit to generation of volatiles for flaming combustion because most of the pyrolysis is completed and the rate has slowed considerably. In a normal atmosphere this steadily decreasing weight loss rate would allow oxygen to diffuse to the char. Then glowing combustion would become the dominant mechanism for weight loss. In addition, because the char has reached a fairly stable condition, 500° C provides a convenient temperature at which the heating rate effects on char yield can be measured. Finally this temperature also provides a common point for comparisons between fuels.

Table 2 presents average char yields for different fuel parts (foliage, wood, stems, bark, and others) exposed to the three heating methods. Table 3 presents char data for individual fuels. The average standard deviation for all replicate runs was ± 0.25 percent. These data are on an ash-free, moisture-free basis, indicating only char formed from organic fuel. The average ash contents are also given in table 3. When the heating rate was increased from 20° to 200° C/min, the char yield decreased, but only by about 1 percent of dry fuel weight. A Student's t test showed that this decrease was not significant at the 0.05 probability level (2 to 3 degrees of freedom) for about 60 percent of the fuels. Thus, the effect of a 10-fold increase in heating rate on char yield was nearly negligible.

Table 2.--*Summary of the effect of heating rate on char yield from different fuel types*

Fuel type	Percent char[1] at 500° C			
			Preheated furnace	
	20° C/min	200° C/min	30 seconds	50 seconds
Foliage	27.4	26.4	25.7	24.5
Wood	22.0	21.0	19.5	18.8
Stems	25.3	24.8	23.4	22.5
Bark	36.5	34.6	34.4	33.3
Other	27.7	25.9	25.2	24.3
All[2]	26.7	25.7	24.8	23.9

[1] Ash-free, dry weight basis.

[2] Values are the average of all samples tested at the indicated heating rate.

Rapid sample heating with the preheated furnace resulted in less char than both the 20° and 200° C/min rates. The char values measured after 50 seconds should be most comparable to the other heating methods because each was allowed 30 seconds to pyrolyze at the final temperature. An initial 20 seconds was required to reach the final temperature in the preheated furnace. The average difference between char yields for the 20° C/min rate and 50 seconds in the preheated furnace was 2.8 percent. A decrease was significant at the 0.05 level for 95 percent of the fuels studied, confirming the trend seen at 200° C/min. Char yields after 30 seconds, which may be a better measure of the fuel available for glowing combustion, were also given in tables 2 and 3 for comparison.

Table 3.--*Char yield from forest fuels exposed to several heating rates*

Sample number[2]	Percent ash[3]	Percent char[1] at 500° C			
				Preheated furnace	
		20° C/min	200° C/min	30 seconds	50 seconds
		Foliage			
1	4.4	27.8	27.7	27.0	25.9
2	3.6	29.9	29.1	27.6	26.3
3	7.7	25.0	23.6	21.5	20.6
4	2.4	24.6	24.2	22.6	21.4
5	5.5	23.7	23.1	22.7	21.5
6	2.4	28.5	28.5	27.7	26.5
7	3.6	26.0	25.6	25.2	24.1
8	1.6	28.9	28.3	27.1	26.2
9	4.2	33.3	31.1	30.8	29.8
10	2.9	26.2	25.4	24.3	23.3
11	4.1	25.9	24.6	24.1	23.0
12	5.7	27.1	26.1	25.0	23.8
13	5.3	28.3	28.0	27.1	26.0
14	4.3	28.2	27.1	26.2	25.0
		Wood			
15	0.5	21.7	21.2	19.9	19.3
16	.2	20.9	20.0	19.1	18.3
17	.6	20.4	19.2	17.9	17.3
18	.4	15.2	14.0	12.9	12.4
19	.2	20.3	19.0	18.0	17.3
20	.2	23.2	21.5	20.5	19.7
21	.4	19.1	18.3	17.2	16.5
22	.3	19.9	19.3	18.2	17.4
23	.2	19.7	18.8	17.9	17.1
24	.2	21.7	20.8	20.0	19.2
25	.5	40.0	39.3	37.8	36.8
		Stems			
26	2.8	26.7	25.8	22.1	21.6
27	7.8	25.6	25.9	24.9	24.0
28	2.2	21.9	21.5	19.9	19.1
29	2.9	27.2	27.2	26.3	25.1
		Bark			
30	17.1	27.1	26.8	26.6	25.4
31	1.7	36.5	36.1	34.2	33.1
32	.8	46.2	43.9	43.7	42.6
33	1.6	36.3	34.8	33.5	32.2
		Other			
34	6.8	21.3	20.6	19.1	18.5
35	9.4	24.0	23.5	21.3	20.5
36	9.6	38.1	38.0	37.3	36.3
37	5.4	32.6	31.8	29.6	28.7
38	32.7	35.6	34.4	33.4	32.4
39	31.7	37.7	38.4	48.1	36.4
40	.1	4.9	4.2	4.1	3.8

[1] Ash-free, dry weight basis.
[2] Numbers refer to samples described in table 1.
[3] Average of ash percentages measured for all heating conditions.

The data in tables 2 and 3 show that char yield from typical forest fuels is only a weak function of heating rate above 20° C/min. Increasing the rate by a factor of 50 only decreased the average char by 2.8 percent, based on original organic fuel. All five fuel types showed essentially the same trend. Changes for wood samples, with high cellulose content, were not appreciably different from bark, foliage, or stems. Even for pure cellulose, the char yield only changed from 4.9 percent to 3.8 percent for the 20° C/min and preheated furnace method, respectively. Although prolonged heating of cellulose at low temperatures increases char yield (Broido and Nelson 1975), the effect was greatly reduced at the higher rates used in this study.

It is not clear which of the existing theories on char formation and the effect of heating rate would best explain the effect observed for these forest fuels. The secondary charring of volatiles, proposed by Lewellen and others (1977), can adequately explain the small effect of heating rate on charring of forest fuels. With this mechanism, char yield depends on residence time of volatile products within the pyrolyzing matrix. Residence times are reduced when the products are formed at the higher reaction temperatures resulting from higher heating rates. However, it seems unlikely that char can only be formed by secondary reactions of volatile products. The large char yields from most forest fuels, compared to cellulose (up to 46 percent for ponderosa pine bark), suggest that primary char forming reactions of some fuel components are also important. Additional studies at higher temperatures and higher heating rates would be needed to support this latter mechanism.

CONCLUSIONS

The data in table 3 show that heating rate is not a critical parameter in measuring relative char yields from forest fuels. If fuels are ranked in order of increasing char yield, and differences smaller than 1 percent are ignored, their order does not depend on heating rate. Comparisons obtained by thermogravimetric analysis at slower heating rates should be valid at the higher heating rates experienced in spreading fires. In addition, the TG experiments give other details of the volatile generation process which may be related to ignition or flammability characteristics of the fuels. Parameters such as weight loss rates and decomposition temperatures can be related to burning rates (Philpot and Mutch 1966) or to fire retardant effectiveness (George and Susott 1971).

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